METAL-SEMICONDUCTOR-METAL (MSM) HETEROJUNCTION DIODE

CLAIM OF PRIORITY

[0001] This application claims the benefit of priority under 35 U.S.C. §119(e) to provisional U.S. Patent Application No. 61/687,163, filed on Apr. 19, 2012, the entire contents of which are hereby incorporated by reference.

FIELD OF USE

[0002] The present disclosure relates generally to diodes, and specifically to high speed diode devices.

BACKGROUND

[0003] Typical diodes have a cut-off frequency in the high gigahertz (GHz) or low terahertz (THz) range (e.g., a cut-off frequency less than 10 THz), which set a limit on the operating frequency range. Examples of such diodes include a Schottky diode, a backward tunneling diode, and a metal-insulator-metal (MIM) tunneling diode.

[0004] High-speed diodes, e.g., diodes having a cut-off frequency greater than 10 THz, are key elements for a broad range of applications. For example, a high speed diode combined with an optical antenna (referred as a rectenna) can lead to operations in optical frequencies, such as coherent generation and detection of infrared to far-infrared signals, and rectification of solar radiation for energy conversion. In these operations, the optical antenna is responsible for light collection and emission, while the diode must operate fast enough to match the corresponding optical frequencies and possess other required current-voltage (I-V) characteristics, such as excellent nonlinearity and rectification. Thus, obtaining highly nonlinear diodes having a cut-off frequency and operational speed higher than 100 THz is of profound technological and scientific importance.

SUMMARY

[0005] The present disclosure describes apparatus and methods relating to a metal-semiconductor-metal (MSM) heterojunction diode. A thickness of a crystalline semiconductor layer of an MSM diode is less than or comparable to a mean free path of charge carriers emitted into a semiconductor layer of the MSM diode, which can result in near ballistic carrier transport across the semiconductor layer and lead to an exceptionally high thermionic emission current density while exhibiting excellent nonlinearity and rectification. A series resistance of the MSM diode can be extremely small. A cut-off frequency of the MSM diode can exceed 100 THz.

[0006] In one aspect of the present disclosure, a diode comprises: a semiconductor layer having a first side and a second side opposite the first side, the semiconductor layer having a thickness between the first side and the second side, the thickness of the semiconductor layer being based on a mean free path of a charge carrier emitted into the semiconductor layer; a first metal layer deposited on the first side of the semiconductor layer; and a second metal layer deposited on the second side of the semiconductor layer.

[0007] Implementations of the disclosure can include one or more of the following features. The thickness of the semiconductor layer may be comparable to or less than the mean free path of the charge carrier emitted into the semiconductor layer. In some implementations, the diode may have a cut-off frequency exceeding 100 THz. In some implementations, the diode may have a cut-off frequency exceeding 1000 THz. In some implementations, the first metal layer and the second metal layer may be the same metal. In some implementations, the first metal layer may be a first metal, the second metal layer may be a second metal, and the first metal and the second metal may be different metals. An interface of the semiconductor layer may be degenerately doped for creation of an ohmic contact. The semiconductor layer may include one or more single crystalline semiconductors, polycrystalline semiconductors, or a combination. The semiconductor layer may include one or more semiconductors such as silicon (Si), germanium (Ge), silicon germanium (SiGe), aluminum antimonide (AlSb), gallium antimonide (GaSb), gallium arsenide (GaAs), indium antimonide (InSb), indium arsenide (InAs), indium gallium arsenide (InGaAs), gallium nitride (GaN), indium phosphide (InP), cadmium selenide (CdSe), cadmium telluride (CdTe), cadmium sulfide (CdS), zinc selenide (ZnSe), zinc telluride (ZnTe), zinc sulfide (ZnS), zinc oxide (ZnO), titanium oxide (TiO_2), lead sulfide (PbS), and lead telluride (PbTe). The first metal layer and the second metal layer each may include at least one metal selected from the group consisting of silver (Ag), aluminum (Al), gold (Au), cobalt (Co), chromium (Cr), copper (Cu), gadolinium (Gd), hafnium (Hf), indium (In), iridium (Ir), magnesium (Mg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), palladium (Pd), platinum (Pt), rhodium (Rh), tantalum (Ta), titanium (Ti), tungsten (W), and zinc (Zn). The diode may be a metal-semiconductor-metal heterojunction diode (MSM diode), where the MSM diode further comprises: a heterojunction between the semiconductor layer and one or more of the first metal layer and the second metal layer.

[0008] In another aspect of the present disclosure, a method for fabricating a diode comprises: providing a semiconductor having a first side and a second side opposite the first side, the semiconductor having a thickness between the first side and the second side, the thickness being based on a mean free path of a charge carrier emitted into the semiconductor; depositing a first metal on the first side of the semiconductor; and depositing a second metal on the second side of the semiconductor.

[0009] Implementations of the disclosure can include one or more of the following features. Obtaining the semiconductor may include obtaining a substrate of layered materials that includes a layer comprising the semiconductor and one or more other layers comprising at least one material that is different from the semiconductor, bonding the first side of the semiconductor to a carrier wafer to position the first metal between the semiconductor and the carrier wafer, and removing the one or more other layers to expose the second side of the semiconductor. In some implementations, depositing the first metal on the first side of the semiconductor may include patterning the first side of the semiconductor. In some implementations, depositing the first metal on the first side of the semiconductor may include depositing the first metal directly onto the first side of the semiconductor as a uniform metal film. Bonding the first side of the semiconductor to the carrier wafer may include bonding the first side of the semiconductor to the carrier wafer using an adhesive. The method may include degenerate doping of a surface of the semiconductor layer for creation of an ohmic contact.

[0010] In yet another aspect of the present disclosure, a p-type metal-semiconductor-metal heterojunction diode (MSM diode) comprises: a silicon layer having a first side and a second side opposite the first side, a surface of the first side being doped with boron at a surface concentration of 1×10^{20}